Journal of Dentistry 148 (2024) 105150

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

The effect on the performance of a dynamic navigation system of superimposing a standard tessellation language (STL) file obtained with an intraoral scan on a cone beam computer tomograph (CBCT). An experimental in vitro study

Adrià Jorba-García [a,d], Víctor Ruiz-Romero [a], Jose Javier Bara-Casaus [b,e], Octavi Camps-Font [c,d], Maria Ángeles Sánchez-Garcés [c,d], Rui Figueiredo [c,d,*], Eduard Valmaseda-Castellón [c,d]

[a] Master of Oral Surgery and Implantology, Faculty of Medicine and Health Sciences, University of Barcelona, Barcelona, Spain
[b] Dental and Maxillofacial Institute at the University Hospital Sagrat Cor, Barcelona, Spain
[c] Oral Surgery, Faculty of Medicine and Health Sciences, University of Barcelona, Spain
[d] Researcher at the IDIBELL Institute, Barcelona, Spain
[e] Head of the department of oral and maxillofacial surgery, University Hospital of Mutua Terrassa, Terrassa, Spain

ARTICLE INFO

Keywords:
Computer-assisted surgery
Dental implants
Surgical navigation systems
Implant-supported dental prosthesis
Intraoral scanner
Accuracy

ABSTRACT

Objectives: To compare the accuracy and operative time of implant placement using a dynamic computer assisted implant surgery (dCAIS) system based on a cone beam computer tomography (CBCT) image, with and without superimposing a standard tessellation language (STL) file of an intraoral scan of the patient.
Methods: Ten identical resin models simulating an upper maxilla with posterior edentulism were assigned to two groups. In the CBCT+STL group, a CBCT file and an intraoral STL file were superimposed and used for registration; in the CBCT group, registration was performed using CBCT images. Six implants were placed in each model using the Navident® dynamic navigation system. Anatomy registration was performed by tracing fiducial points on the CBCT or STL image, depending on the group. Preoperative and postoperative CBCT images were overlaid to assess implant placement accuracy.
Results: Sixty implants were analyzed (30 implants in each group). 3D platform deviation was significantly lower (mean difference (MD): 0.17 mm; 95 % confidence interval (CI): 0.01 to 0.23; $P = 0.039$) in the CBCT+STL group (mean: 0.71 mm; standard deviation (SD): 0.29) than in the CBCT group (mean: 0.88 mm; SD: 0.39). The remaining accuracy outcome variables (angular deviation MD: -0.01; platform lateral deviation MD: 0.08 mm; apex global MD: 0.01 mm; apex depth MD: 0.33 mm) and surgery time (MD: 3.383 min.) were similar in both groups ($p > 0.05$).
Conclusions: The introduction of an intraoral scan (STL) seems to reduce deviations slightly in dental implant placement with dCAIS systems. However, the clinical repercussion of this improvement is questionable.
Clinical significance: Superimposing an intraoral scan on the CBCT image does not seem to increase the accuracy of dCAIS systems but can be useful when radiographic artifacts are present.

1. Introduction

The use of cone beam computer tomography (CBCT) in implant dentistry has allowed surgeons to make accurate assessments of the available bone and the position of anatomic structures. Thus, the use of CBCT has reduced the risk of complications and has facilitated preoperative prosthetic-driven implant planning [1-3].

Nowadays, computer assisted implant surgery (CAIS) is a reliable treatment approach for dental implant placement. Several studies have shown that these techniques are accurate, predictable, and allow a minimal approach in implant dentistry [4-9]. Two CAIS approaches should be differentiated: Static CAIS (sCAIS) uses a rigid guide with

* Corresponding author at: Facultat de Medicina i Ciències de la Salut, Campus de Bellvitge, Universitat de Barcelona (UB), Pavelló de Govern; 2a planta, Despatx 2.9, C/ Feixa Llarga s/n, E-08907 L'Hospitalet de Llobregat, Spain.
E-mail address: ruibarbosa@ub.edu (R. Figueiredo).

https://doi.org/10.1016/j.jdent.2024.105150
Received 23 February 2023; Received in revised form 15 September 2023; Accepted 21 June 2024
Available online 22 June 2024

sleeves to transfer the planned position of the dental implants to the mouth, while dynamic CAIS (dCAIS) uses tomographic images in a computer display to show the real-time position of the burs and the implant relative to the virtual preoperative plan [10-12].

Both approaches require a CBCT scan to plan the implant position preoperatively. Although CBCT provides excellent bone anatomy detail, the anatomy of the teeth and soft tissues is not shown precisely enough to manufacture a surgical guide [10,13]. Thus, sCAIS systems require the CBCT images to be merged with the information acquired through scanning the intraoral anatomy, either with an intraoral scan or by scanning a stone cast [14]. This process achieves an adequate fit of the guide in the mouth and, therefore, an accurate drilling sequence and implant placement [13].

In contrast, dCAIS systems generally do not require preoperative models of the dental anatomy or the soft tissues. The registration concept in dCAIS systems is slightly different, as an "image-to-patient registration" is performed [10,15]. This process, which consists of virtually merging the CBCT images with the real patient's anatomy, can be carried out by using a radiographic marker placed on the patient's teeth before the CBCT, or by selecting different fiducial points (usually teeth) on the CBCT and then tracing them on the patient (markerless pair-point registration). Specific software will then recognize the patient's position in relation to the CBCT images [15]. This tracing registration can be done on CBCT images or in a merged standard tessellation language (STL) file.

Since the visualization of the anatomy of the remaining teeth is usually not excellent in CBCT [16-19], the tracing of fiducial markers might be imprecise, and this could affect the accuracy of dCAIS systems. Nevertheless, there appear to be no studies on this topic. Thus, the aim of this in vitro randomized study was to assess the accuracy of implant placement using a dCAIS system with and without overlaying an intraoral scan (STL file) of the model on the CBCT registration. The main hypothesis was that superimposing a STL file obtained with an intraoral scan onto the CBCT files would increase the accuracy of the dCAIS system during implant placement.

2. Materials and methods

A randomized in-vitro study was performed to assess the accuracy of Navident® navigation system v. 3.0.3 (Navident®, ClaroNav Technology Inc.®, Toronto, Canada) using 2 different registration methods: in the CBCT group, only the CBCT images were used for patient registration, while in the CBCT+STL group, registration was performed using CBCT images overlaid with an STL file of the model. The CONSORT guidelines [20] were followed whenever possible throughout the study. Fig. 1 shows the implant placement steps for each group.

Ten identical customized resin models (BoneModels®, Castellón de la Plana, Spain) simulating bilateral posterior maxillary edentulism (from the first premolar to the second molar) were employed in this study. Five models were allocated to each group. All the models were placed in a preclinical learning dental simulator with limited mouth opening and with facial soft tissues simulating a real clinical scenario (Frasaco GmbH, Tettnang, Germany) (Fig. 2).

The sample size was calculated using G*Power v.3.1.3 software (Heinrich- Heine Universität, Dusseldorf, Germany), based on the assumption that a difference of 0.5 mm in the depth deviation would be clinically significant. Considering a common standard deviation (SD) of 0.47 mm [21], an allocation ratio of 1:1, a risk of 0.05, and a power of 80 %, 30 implants (15 implants per group) were required. Since the implants were not independent due to the two-level data structure (model and implant), the number of models needed to be corrected. Assuming an intrasubject correlation of 0.5 (moderate) and six implants for each model, 60 implants (10 models) were placed.

2.1. Intervention

A preoperative CBCT scan (Vistavox S, Dürr Dental, Germany) of every model was acquired (94 kV, 9 mA, 0.2 × 0.2 × 0.2 mm voxel size, 110 × 80 mm FOV). The models were fixed with a customized platform to avoid movement during scanning. Additionally, the 5 models allocated to the CBCT + STL group were scanned with an intraoral device (3Shape TRIOS® 3D scanner, 3Shape A/S® Copenhagen, Denmark).

All the procedures were performed by a clinician with 4 years' prior experience in dCAIS (A.J-G). The surgeon placed a total of 60 implants (Ocean 4 × 10 mm dental implants, Avinent Implant System, Santpedor, Spain) following the drilling protocol recommended by the manufacturer (guide drill, pilot drill ø1.6 mm, ø1.6–2.4 mm drill, ø 2–3.3 mm drill and ø 2.2–3.8 mm drill).

Six implants were planned in each model (3 per side) in the first premolar, first molar and second molar positions [implant positions (FDI World Dental Federation notation): 14, 16, 17, 24, 26 and 27]. The position of the virtual crowns was considered when deciding the implant positions and a virtual wax up was made using software tools.

2.1.1. CBCT group

Digital imaging and communication in Medicine (DICOM) files of the

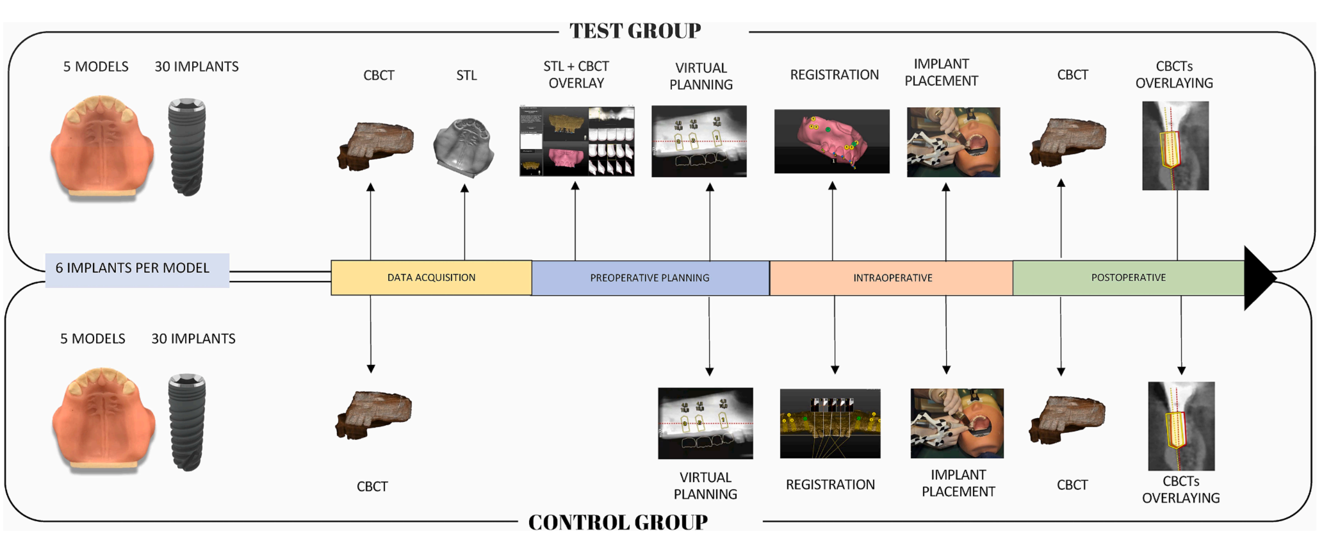

Fig. 1. Infographic showing all the steps for each study group (CBCT group and CBCT + STL group). A total of 60 implants were placed in 10 models. STL: Standard Tessellation Language (intraoral scan files); CBCT: cone beam computer tomography.

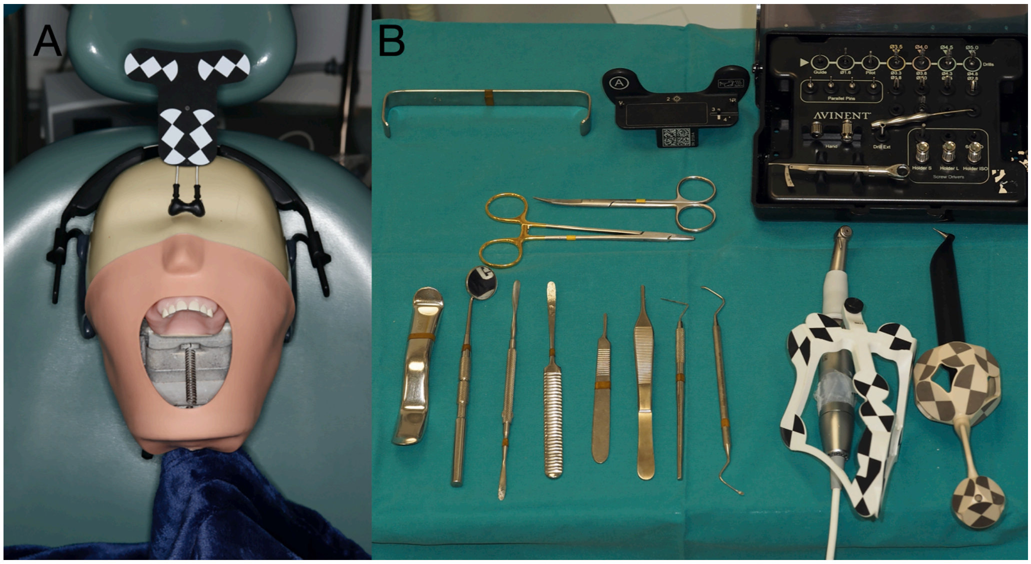

Fig. 2. Preclinical simulation scenario. A. Phantom head with optical markers. The patient optical marker was a head mounted device supported on the nasion, head, and ears. B. Surgical field with oral surgery instruments, handpiece with optical marker, tracer with optical markers and drill axis and tip calibrator.

CBCT scans were uploaded to the navigation system software (Navident ®, ClaroNav Technology Inc. ®, Toronto, Canada).

Optical markers were attached to the handpiece and dental simulator before the procedure (Fig. 2). The optical marker on the patient was a head mounted device supported on the nasion, top of the head, and ears; while the handpiece optical marker was screwed onto a metallic abutment attached to the handpiece. In the registration process, the clinician could select any five fiducial points on the clearest incisal edges or cusp tips of the remaining teeth in the CBCT image. To achieve accurate registration for all the implants, the fiducial points were selected as far apart as possible. Using a probe with an optical marker (tracer) (the instrument on the right in Fig. 2B), the fiducial points were then traced on the resin model. Following successful completion of registration, its accuracy was assessed by touching several points with the tracer on the model and checking the real time feedback from the navigation system (Fig. 3 and Fig. 4A).

2.1.2. CBCT + STL group

In this group, both the CBCT (DICOM) and intraoral scan (STL) data files were uploaded to the Navident ® software. Dental implant planning and the placement of the optical markers were performed following the method described for the CBCT group (Fig. 2).

The registration process consisted of selecting five fiducial points on the STL file and tracing them on the dental model with the tracer (Figs. 3 and 4B).

Fig. 3. Markerless pair-point trace registration, touching several model teeth with the tracer with optical markers.

2.1.3. Surgical procedure

A crestal incision was performed and an envelope flap was raised. The drill tip and axis were calibrated with a specific device and the implant site was prepared using the navigation system (Figs. 5A and 5B). Accuracy was checked by placing the drill tip on a cusp before each step in the drilling sequence. If any inaccuracy was detected, most probably due to involuntary optical marker movements, re-registration was performed, and the fiducial points were traced anew. Implant placement was also guided by the dCAIS system.

A postoperative CBCT scan was performed on all the models with the same settings as in the preoperative scan. A second blinded researcher (V.R-R) overlaid the two CBCT scans (pre- and postoperative), using EvaluNav software (Navident®, ClaroNav Technology Inc.®, Toronto, Canada), to check the implant placement accuracy (planned position vs. final position).

2.2. Blinding and randomization

Due to the nature of the study, it was not possible to blind the surgeon, as the navigation images were different. The researcher responsible for overlaying the preoperative and postoperative CBCTs and gathering the accuracy data was blinded, since the group variable was coded.

The treatment sequence (CBCT or CBCT + STL) was randomized using the www.randomization.com website (accessed in December 2021).

2.3. Outcomes

For each implant, five accuracy variables were registered:

- Platform three-dimension (3D) deviation (in mm): global deviation at the entry point of the dental implant, measured in the three spatial dimensions.

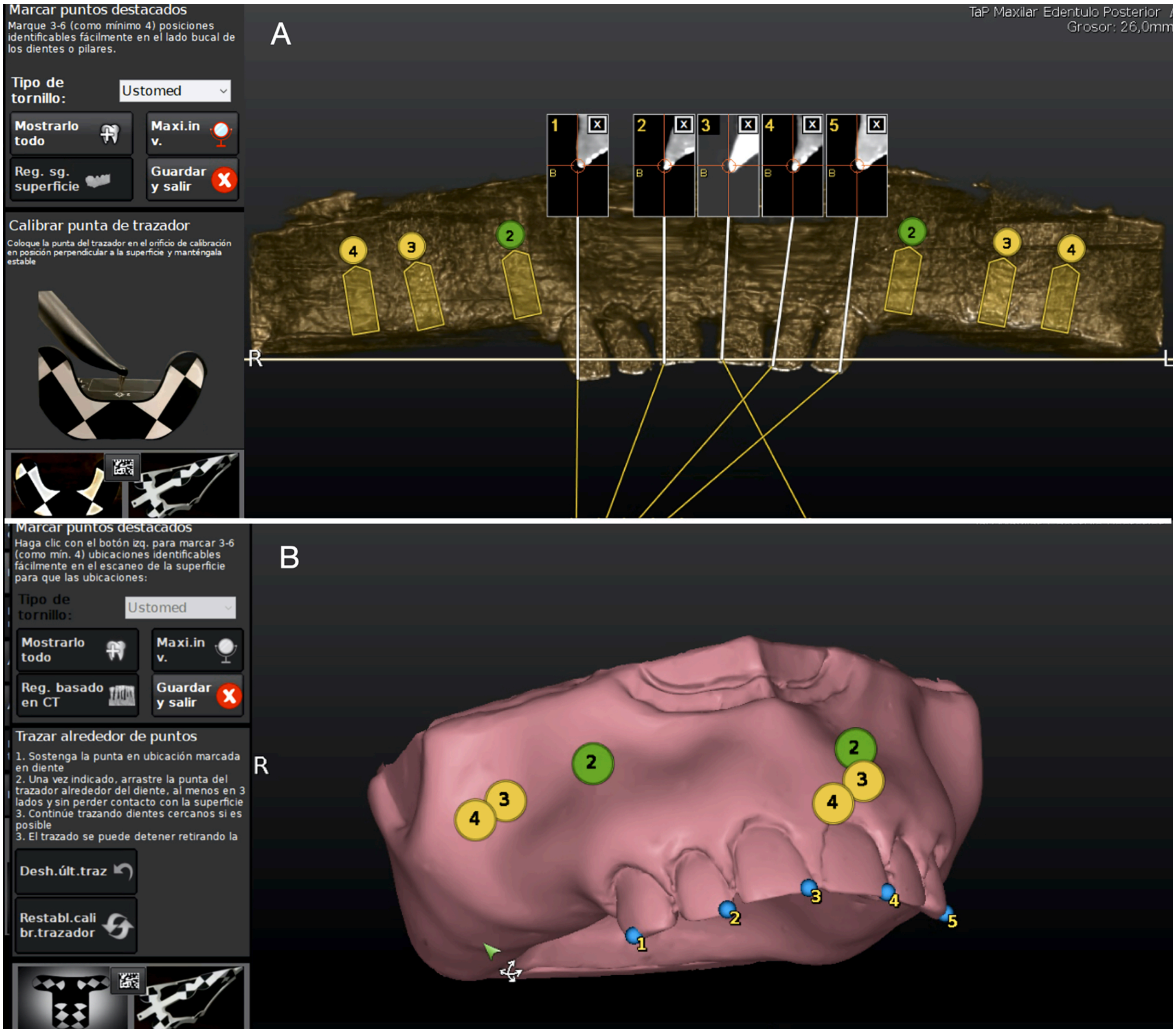

Fig. 4. Screen view of markerless pair-point trace registration with Navident ® software. A. Cone beam computer tomography (CBCT) pair-point trace registration. B. Standard Tessellation Language (STL) pair-point trace registration.

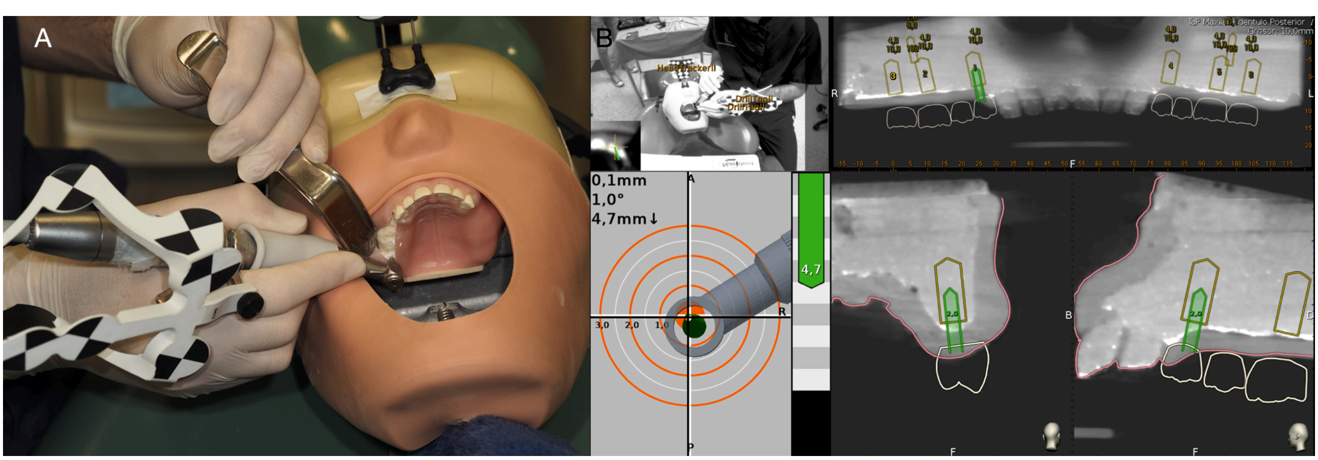

Fig. 5. Implant placement using the Navident dynamic computer assisted guidance (dCAIS) system. A. View of the surgical procedure using artificial models and the phantom head with optical markers. B. Computer software interface during the surgical procedure.

- Platform two-dimension (2D) deviation (in mm): horizontal deviation of the dental implant at the entry point in an occlusal view, without considering depth deviation.
- Apex 3D deviation (in mm): global deviation at the apex of the dental implant, measured in the three spatial dimensions.

- Apex depth deviation (in mm): depth or vertical deviation of the apex of the dental implant
- Angular deviation (in degrees): angular deviation between the two axes of the implants.

Since manual selection of several points is required to overlap the preoperative and postoperative CBCT images, intraexaminer agreement and consistency were tested in 3 randomly selected models (90 measurements). The measurements were repeated after 2 weeks. The intraclass correlation coefficient (ICC) was 0.82 (95 %CI: 0.71 to 0.88; $P < 0.001$) for absolute agreement.

The time spent performing the following procedures was also registered: CBCT + STL overlaying, registration and implant placement. The number of additional registrations needed due to any inaccuracy was also recorded.

2.4. Statistical analysis

The normality of scale variables was explored using the Shapiro-Wilk test and through visual analysis of the P-P plot and box plot. Where normality was rejected, the interquartile range (IQR) and median were calculated. Where distribution was compatible with normality, the mean and SD were used. Differences between groups of scale variables were explored using parametric (Student's t-test for independent or paired samples) or nonparametric tests (Mann-Whitney *U* test or Wilcoxon signed-rank test).

Multilevel linear regression models were conducted to evaluate accuracy outcomes based on the guidance method using generalized estimating equations (GEE). The GEE method was used to account for the fact that repeated observations (several implants) were available in the same model. Group (CBCT or CBCT+STL), region (premolar or molar), implant position (first premolar, first molar and second molar) and the interaction between them were included as predictor variables. Adjusted beta coefficients for linear regression models including 95 % confidence intervals (CIs) were obtained from the Wald $\chi 2$ statistic.

SPSS version 27 (SPSS Inc., Chicago, IL, USA) was used for the statistical analyses. The level of significance was set at $P < 0.05$.

3. Results

Thirty dental implants were analyzed in each group. The results of the accuracy variables are summarized in Table 1. A statistically significant reduction in deviation was found in the CBCT+STL group regarding the mean global 3D platform deviation (Mean difference (MD): 0.17 mm; 95 % CI: (0.01 to 0.34); $P = 0.039$). No statistically significant differences were observed in the remaining accuracy variables (Table 1, Fig. 6). The CBCT group had a mean angular deviation of 2.29° (SD: 2.33), a mean platform lateral deviation of 0.63 mm (SD: 0.34), a mean apex global deviation of 0.97 mm (SD: 0.48) and a mean apex depth deviation of 0.50 mm (SD: 0.55). The CBCT + STL group had a mean angular deviation of 2.30° (SD: 1.91), a mean platform lateral deviation of 0.54 mm (SD: 0.30), a mean apex global deviation of 0.95 mm (SD: 0.35) and a mean apex depth deviation of 0.33 mm (SD: 0.25).

Table 1
Summary of accuracy variables.

Accuracy variable	CBCT Mean (SD)	CBCT+STL Mean (SD)	MD (95 %CI)	P-value
Angular (°)	2.29 (2.33)	2.30 (1.91)	−0.01 (−1.09 to 1.07)	0.989
Platform global (mm)	0.87 (0.38)	0.69 (0.27)	0.17 (0.01 to 0.34)	0.039*
Platform lateral (mm)	0.63 (0.34)	0.54 (0.30)	0.08 (−0.06 to 0.23)	0.259
Apex global (mm)	0.97 (0.48)	0.95 (0.35)	0.01 (−0.19 to 0.22)	0.893
Apex depth (mm)	0.50 (0.55)	0.33 (0.25)	0.17 (−0.05 to 0.40)	0.401

CBCT: Cone beam computer tomography (CBCT); STL: Standard Tessellation Language; SD: Standard deviation; MD: Mean difference (CBCT – CBCT+STL); 95 %CI: 95 % Confidence interval.
Note: MD adjusted according to generalized estimating equations (GEE), considering other covariates.

The interaction between group (CBCT or CBCT+ STL) and implant site (premolar, first molar or second molar) did not yield any statistically significant difference for any of the accuracy variables assessed ($P > 0.05$), and similar results were obtained in the different implant site positions (Fig. 6).

The time employed in placing the 6 implants in each model was similar in both groups ($P = 0.748$). A mean of 29.2 min (SD: 5.04) was necessary in the CBCT group and a mean of 28.1 min (SD: 5.56) in the CBCT+STL group. Likewise, the registration time was also similar in both groups (CBCT+STL group: 1.83 min vs. CBCT group: 1.56 min; $P = 0.459$). A mean of 2.44 min (SD: 0.46) was needed to superimpose the CBCT and the STL file. *Re*-registration due to inaccuracies was required in 4 models (3 out of 5 in the CBCT group and 1 out of 5 in the STL+CBCT group; $P = 0.17$) (Table 2).

4. Discussion

The main aim of this trial was to assess whether performing an intraoral scan improves the accuracy of dCAIS systems. To the best of our knowledge, it is the first study to address this issue. It has shown that this procedure improves the location of the implant platform ($P = 0.039$) in comparison with the standard technique. Nevertheless, since the improvement in accuracy was only 0.17 mm (95 %CI: 0.01 to 0.34), it cannot be considered clinically relevant in the present simulation scenario. Thus, in the authors' view, the accuracy outcomes of both groups are similar, indicating that there is no need to merge the CBCT images with STL files. Nevertheless, the introduction of an STL file could significantly increase the accuracy of dCAIS if low quality CBCT scans are used or when radiographic artifacts are present.

In sCAIS and dCAIS, the registration process is crucial to achieve precise results. Nevertheless, this procedure is performed in totally different ways. In sCAIS, registration consists in merging STL files (intraoral scan data) and a DICOM file (radiographic data from the CBCT scan) to accurately reproduce the dental anatomy, in order to fabricate splints that fit the patient perfectly [22]. This process has been described thoroughly in the literature [13,23]. A potential problem is that radiographic artifacts, such as metallic restorations, orthodontic appliances, or other dental implants, can distort the images [13,14,24,25]. However, dCAIS registration requires space coordinates of the patient's position to merge this virtually with the CBCT images [15]. Hence, an intraoral scan is not mandatory. Instead, fiducial markers or points must be selected and placed [26]. In general, dCAIS systems use radiographic fiducial markers, attached to intraoral splints or devices, which are automatically detected by the software. During the surgical procedure, the splint with the optical markers must be placed in exactly the same location so that the software automatically registers the patient's position [27,28].

Recently, the introduction of a tracing technology that does not require radiographic fiducial markers has enabled registration using different anatomical fiducial points on the patient (usually located on the remaining teeth). Thus, this process does not require placing an intraoral device, and prior CBCT scans of the patient (without markers) can be used to perform the guided surgery [29,30]. Nevertheless, certain limitations need to be considered. Firstly, in fully edentulous patients, it might be difficult to select fiducial points. In these situations, placement of three to six miniscrews before the CBCT scan allows point-to-point registration using the head of the screw as a reference [31]. Another option is to fabricate a radiographic splint with at least three

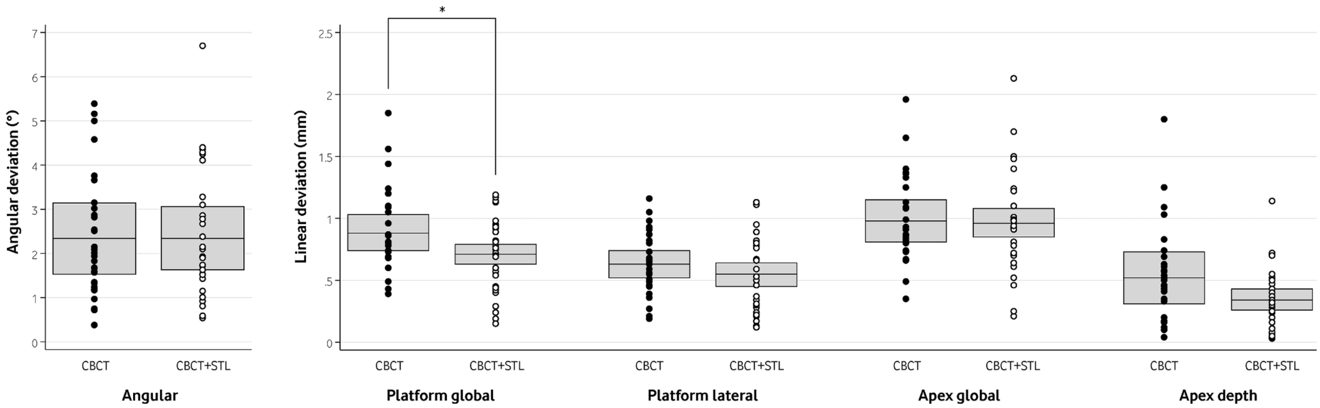

Fig. 6. Box and scatter plots of angular and linear deviations for the CBCT and CBCT+STL groups. For each box, the bold interior line shows the mean, and the edges of the box are estimates of the lower and upper 95 % confidence intervals. STL: Standard Tessellation Language (intraoral scan files); CBCT: cone beam computer tomography. °: degrees, mm: millimeters.

Table 2
Mean time recording for overlapping, registration, surgery, and recalibration.

Accuracy variable	CBCT Mean (SD)	CBCT+STL Mean (SD)	MD (95 %CI)	P-value
Overlaying (minutes) Mean (SD)	–	2.4 (0.47)	–	–
Registration (minutes) Mean (SD)	1.6 (0.5)	1.8 (0.6)	0.253 (−1.004 to 0.498)	0.459
Surgery (minutes) Mean (SD)	26.9 (4.5)	23.52 (2)	3.383 (−3.125 to 9.925)	0.265
Recalibrations (minutes) Mean (SD)	1.2 (0.2)	1.6*	–	–
TOTAL (minutes) Mean (SD)	29.2 (5.0)	28.1 (5.6)	1.113 (−5.521 to 8.862)	0.748

CBCT: Cone beam computer tomography (CBCT); STL: Standard Tessellation Language; SD: Standard deviation; MD: Mean difference (CBCT – CBCT+STL); 95 %CI: 95 % Confidence interval.
* SD and 95 % CI could not be calculated since only one case in the CBCT+STL group required recalibration.

radiographic fiducial marker points.

Several factors could limit the quality and definition of a CBCT scan. Radiographic artifacts are especially relevant and might hinder correct registration, since the tooth anatomy (edges and cusps) and microscrews might not be fully recognizable. Thus, in patients with reconstructions, brackets or prosthetic rehabilitations, a specific device with radiopaque landmarks or at least three microscrews might be placed before performing the CBCT scan and then traced during surgery. In these cases, overlaying the STL and DICOM files corrects radiographic artifacts and allows point-to-point registration without the introduction of any specific device. Ideally, for accurate overlay, at least three points should be selected in both files, creating a wide triangle (for example, points located on one anterior tooth and two posterior teeth) [25]. Hence, if only unilateral or anterior teeth remain, the placement of additional landmarks (bone anchored or adhesive) should be considered [32,33]. In addition, it should be noted that tooth mobility might also result in inaccurate registration [29].

Pei et al. [34] compared 3 different markers (micro-screws, tooth cusps and intraoral devices) in an in vitro study and concluded that intraoral devices seem to be more accurate (angular deviation of 1.36 (SD:0.54)). It is important to stress that these authors reported high deviations in all groups, in contrast with the outcomes of our study.

The findings of this study confirm that the use of an intraoral scan has limited clinical repercussion, since the accuracy improvement was imperceptible (less than 0.2 mm). Moreover, the alignment between the STL file of the dentition and the CBCT data might be an additional source of inaccuracies. However, this technique can provide additional information (soft tissue thickness and emergence profile) that might improve prosthetic planning [35,36]. The use of an STL file could also present some advantages when radiographic artifacts hinder correct registration on CBCT images. Additionally, while neither statistically significant nor significantly increasing the overall procedure time, re-registration due to inaccuracies was required in 3 out of 5 models in the CBCT group but in only 1 out of 5 in the CBCT + STL group.

It is important to point out that, on some occasions, clinically relevant deviations can occur when using dCAIS systems [5,29]. In the present study, some implants presented angular deviations of more than 5° and lineal deviations of more than 1.5 mm. This is particularly relevant when assessing the apex depth, since these inaccuracies might lead to major complications (for example, inferior alveolar nerve damage). For this reason, a safety margin should always be applied when performing virtual implant placement planning.

This in vitro study has some limitations that should be discussed. In a real clinical scenario, CBCT image quality might be affected by the patient's movements or the presence of metallic artifacts. Also, this study only addressed a specific situation (posterior maxillary edentulism). Thus, future research should assess whether these findings are affected by variables like the number and location of the missing teeth (anterior versus posterior; maxilla versus mandible, single implants versus multiple implants, fully edentulous versus partially edentulous patients, etc.) or by the presence of adjacent metallic elements. Generalization of the results should also be treated with caution if other dCAIS systems are used or less experienced surgeons are involved.

5. Conclusions

Performing an intraoral scan (STL file) of the patient seems to reduce deviations slightly in dental implant placement with dCAIS systems. However, the clinical repercussion of this improvement is questionable. Nonetheless, this procedure might be of interest when radiographic artifacts are present or when information on the soft tissues can provide useful data for prosthetic planning.

Funding

This work was partially supported by the University of Barcelona [XXI Convocatòria d'ajuts per a la recerca per a estudiants de tercer cicle de la UFR d'Odontologia, 2018]. The implants were kindly provided by Avinent SA (Santpedor, Spain). The authors would also like to thank

BoneModels (Castellón de la Plana, Spain) for the development of the customized resin models.

CRediT authorship contribution statement

Adrià Jorba-García: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Víctor Ruiz-Romero:** Investigation, Writing – original draft, Visualization. **Jose Javier Bara-Casaus:** Conceptualization, Resources, Writing – review & editing, Funding acquisition. **Octavi Camps-Font:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization. **Maria Ángeles Sánchez-Garcés:** Methodology, Resources, Writing – review & editing, Supervision. **Rui Figueiredo:** Conceptualization, Methodology, Resources, Writing – review & editing, Project administration, Funding acquisition. **Eduard Valmaseda-Castellón:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The authors declare no conflict of interest directly related with this study. However, the authors would like to state the following conflicts outside the submitted work:

Dr. Rui Figueiredo reports grants, personal fees, and non-financial support from MozoGrau (Valladolid, Spain), Avinent (Santpedor, Spain), Inibsa Dental (Lliçà de Vall, Spain), Dentaid SL (Cerdanyola del Vallés, Spain), non-financial support from Nobel Biocare (Zürich, Switzerland), personal fees from Geistlich Pharma AG (Wolhusen, Switzerland), BioHorizons Iberica (Madrid, Spain), Araguaney Dental (Barcelona, Spain), Septodont (Saint-Maur-des-fossés, France) and Laboratorios Silanes (Mexico city, Mexico) outside the submitted work. Dr. Figueiredo has also participated as a principal investigator in a randomized clinical trial sponsored by Mundipharma (Cambridge, UK) and in another clinical trial as a sub-investigator for Menarini Richerche (Florence, Italy).

Dr. Eduard Valmaseda-Castellón reports grants, personal fees, and non-financial support from MozoGrau (Valladolid, Spain), Avinent (Santpedor, Spain), Inibsa Dental (Lliçà de Vall, Spain), Dentaid SL (Cerdanyola del Vallés, Spain), and personal fees from BioHorizons Iberica (Madrid, Spain) and Laboratorios Silanes (Mexico city, Mexico) outside the submitted work. Dr. Eduard Valmaseda-Castellón has also participated as a principal investigator in a randomized clinical trial sponsored by Geistlich Pharma AG (Wolhusen, Switzerland) and in another clinical trial as a sub-investigator for Mundipharma (Cambridge, UK).

Acknowledgments

The authors are grateful to Mary Georgina Hardinge for English language editing assistance.

References

[1] M.M. Bornstein, W.C. Scarfe, V.M. Vaughn, R. Jacobs, Cone beam computed tomography in implant dentistry: a systematic review focusing on guidelines, indications, and radiation dose risks, Int. J. Oral Maxillofac. Implants. 29 (2014) 55–77, https://doi.org/10.11607/jomi.2014suppl.g1.4.

[2] M. Tallarico, E. Xhanari, Y.J. Kim, F. Cocchi, M. Martinolli, A. Alushi, E. Baldoni, S. M. Meloni, Accuracy of computer-assisted template-based implant placement using conventional impression and scan model or intraoral digital impression: a randomised controlled trial with 1 year of follow-up, Int. J. Oral Implantol. 12 (2019) 197–206.

[3] G. Fokas, V.M. Vaughn, W.C. Scarfe, M.M. Bornstein, Accuracy of linear measurements on CBCT images related to presurgical implant treatment planning: a systematic review, Clin. Oral Implants Res. 29 (2018) 393–415, https://doi.org/10.1111/clr.13142.

[4] A. Jorba-García, A. González-Barnadas, O. Camps-Font, R. Figueiredo, E. Valmaseda-Castellón, Accuracy assessment of dynamic computer-aided implant placement: a systematic review and meta-analysis, Clin. Oral Investig. 25 (2021) 2479–2494, https://doi.org/10.1007/s00784-021-03833-8.

[5] D. Kaewsiri, S. Panmekiate, K. Subbalekha, N. Mattheos, A. Pimkhaokham, The accuracy of static vs. dynamic computer-assisted implant surgery in single tooth space: a randomized controlled trial, Clin. Oral Implants Res. 30 (2019) 505–514, https://doi.org/10.1111/clr.13435.

[6] S.S. Taheri Otaghsara, T. Joda, F.M. Thieringer, Accuracy of dental implant placement using static versus dynamic computer-assisted implant surgery: an in vitro study, J Dent 132 (2023) 104487, https://doi.org/10.1016/j.jdent.2023.104487.

[7] P. Yimarj, K. Subbalekha, K. Dhanesuan, K. Siriwatana, N. Mattheos, A. Pimkhaokham, Comparison of the accuracy of implant position for two-implants supported fixed dental prosthesis using static and dynamic computer-assisted implant surgery: a randomized controlled clinical trial, Clin Implant Dent Relat Res 22 (2020) 672–678.

[8] M. Romandini, E. Ruales-Carrera, S. Sadilina, C.H.F. Hämmerle, M. Sanz, Minimal invasiveness at dental implant placement: a systematic review with meta-analyses on flapless fully guided surgery, Periodontol 91 (2023) (2000) 89–112, https://doi.org/10.1111/prd.12440.

[9] Y. Feng, Z. Su, A. Mo, X. Yang, Comparison of the accuracy of immediate implant placement using static and dynamic computer-assisted implant system in the esthetic zone of the maxilla: a prospective study, Int. J. Implant Dent. 13 (2022) 65, https://doi.org/10.1186/s40729-022-00464-w.

[10] M. Vercruyssen, T. Fortin, G. Widmann, R. Jacobs, M. Quirynen, Different techniques of static/dynamic guided implant surgery: modalities and indications, Periodontol 66 (2014) (2000) 214–227, https://doi.org/10.1111/prd.12056.

[11] A. Guentsch, J. Bjork, R. Saxe, S. Han, A.R. Dentino, An in-vitro analysis of the accuracy of different guided surgery systems - They are not all the same, Clin. Oral Implants Res. 34 (2023) 531–541, https://doi.org/10.1111/clr.14061.

[12] X. Yu, B. Tao, F. Wang, Y. Wu, Accuracy assessment of dynamic navigation during implant placement: a systematic review and meta-analysis of clinical studies in the last 10 years, J Dent 30 (2023) 104567, https://doi.org/10.1016/j.jdent.2023.104567.

[13] T. Flügge, W. Derksen, J. te Poel, B. Hassan, K. Nelson, D. Wismeijer, Registration of cone beam computed tomography data and intraoral surface scans – A prerequisite for guided implant surgery with CAD/CAM drilling guides, Clin. Oral Implants Res. 28 (2017) 1113–1118, https://doi.org/10.1111/clr.12925.

[14] M. Tallarico, E. Xhanari, Y.J. Kim, F. Cocchi, M. Martinolli, A. Alushi, et al., Accuracy of computer-assisted template-based implant placement using conventional impression and scan model or intraoral digital impression: a randomised controlled trial with 1 year of follow-up, Int J Oral Implantol 12 (2019) 197–206.

[15] G. Eggers, J. Mühling J, R. Marmulla, Image-to-patient registration techniques in head surgery, Int. J. Oral Maxillofac. Surg. 35 (2006) 1081–1095, https://doi.org/10.1016/j.ijom.2006.09.015.

[16] R. Spin-Neto, A. Wenzel, Patient movement and motion artefacts in cone beam computed tomography of the dentomaxillofacial region: a systematic literature review. Oral Surg. Oral Med. Oral Pathol, Oral Radiol 121 (2016) 425–433, https://doi.org/10.1016/j.oooo.2015.11.019.

[17] K. Kamburoğlu, S. Murat, E. Kolsuz, H. Kurt, S. Yüksel, C. Paksoy, Comparative assessment of subjective image quality of cross-sectional cone-beam computed tomography scans, J. Oral Sci. 53 (2011) 501–508.

[18] V.A. Wanderley, A.F. Leite, K. de Faria Vasconcelos, R. Pauwels, F. Müller-García, K. Becker, M.L. Oliveira, R. Jacobs, Impact of metal artefacts on subjective perception of image quality of 13 CBCT devices, Clin. Oral Investig. 26 (2022) 4457–4466, https://doi.org/10.1007/s00784-022-04409-w.

[19] S.R. Makins, Artifacts interfering with interpretation of cone beam computed tomography images, Dent. Clin. North Am. 58 (2014) 485–495.

[20] K.F. Schulz, D.G. Altman, D. Moher, CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials, BMJ 340 (2010) c332, https://doi.org/10.1136/bmj.c332.

[21] A. Jorba-García, R. Figueiredo, A. González-Barnadas, O. Camps-Font, E. Valmaseda-Castellón, Accuracy and the role of experience in dynamic computer guided dental implant surgery: an in-vitro study, Med. Oral Patol. Oral y Cir. Bucal. 24 (2019) 76–83, https://doi.org/10.4317/medoral.22785.

[22] S. Schnutenhaus, S. Gröller, R.G. Luthardt, H. Rudolph, Accuracy of the match between cone beam computed tomography and model scan data in template-guided implant planning: a prospective controlled clinical study, Clin. Implant Dent. Relat. Res. 20 (2018) 541–549, https://doi.org/10.1111/cid.12614.

[23] S.J. Alhossaini, A.F. Neena, N.O. Issa, H.M. Abouelkheir, Y.Y. Gaweesh, Accuracy of markerless registration methods of DICOM and STL files used for computerized surgical guides in mandibles with metal restorations: an in vitro study, J. Prosthet. Dent. (2022), https://doi.org/10.1016/j.prosdent.2022.09.017. S0022-3913 00636-9.

[24] P. Kiatkroekkrai, C. Takolpuckdee, K. Subbalekha, N. Mattheos, A. Pimkhaokham, Accuracy of implant position when placed using static computer-assisted implant surgical guides manufactured with two different optical scanning techniques: a randomized clinical trial, Int. J. Oral Maxillofac. Surg. 49 (2020) 377–383, https://doi.org/10.1016/j.ijom.2019.08.019.

[25] Y. Do Choi, H.N. Mai, H.Y. Mai, J.H. Ha, L.J. Li, D.H. Lee, The Effects of Distribution of Image Matched Fiducial Markers on Accuracy of Computer-Guided Implant Surgery, J. Prosthodont. 29 (2020) 409–414, https://doi.org/10.1111/jopr.13171.

[26] A.F. de Geer, S.G. Brouwer de Koning, M.J.A. van Alphen, S. van der Mierden, C. L. Zuur, F.W.B. van Leeuwen, A.J. Loeve, R.L.P. van Veen, M.B. Karakullukcu, Registration methods for surgical navigation of the mandible: a systematic review, Int. J. Oral Maxillofac. Surg. 51 (2022) 1318–1329, https://doi.org/10.1016/j.ijom.2022.01.017.

[27] C.A. Aydemir, V. Arisan, Accuracy of dental implant placement via dynamic navigation or the freehand method: a split-mouth randomized controlled clinical trial, Clin. Oral Implants Res. 31 (2020) 255–263, https://doi.org/10.1111/clr.13563.

[28] P. Boeckx, H. Essig, H. Kokemuller, F. Tavassol, N.C. Gellrich, G.R.J. Swennen, Presentation and Evaluation of a Modified Wax-Bite Dental Splint for Surgical Navigation in Craniomaxillofacial Surgery, J. Oral Maxillofac. Surg. 73 (2015) 2189–2195, https://doi.org/10.1016/j.joms.2015.03.057.

[29] L.V. Stefanelli, G.A. Mandelaris, B.S. DeGroot, G. Gambarini, F. De Angelis, S. Di Carlo, Accuracy of a Novel Trace-Registration Method for Dynamic Navigation Surgery, Int. J. Periodontics Restorative Dent. 40 (2020) 427–435, https://doi.org/10.11607/prd.4420.

[30] E.T. Scheyer, G.A. Mandelaris, M.K. McGuire, M.A. AlTakriti, L.V. Stefanelli, Implant Placement Under Dynamic Navigation Using Trace Registration: case Presentations, Int. J. Periodontics Restorative Dent. 40 (2020) 241–248, https://doi.org/10.11607/prd.4479.

[31] L.V. Stefanelli, G.A. Mandelaris, A. Franchina, N. Pranno, M. Pagliarulo, F. Cera, F. Maltese, F. De Angelis, S. Di Carlo, Accuracy of dynamic navigation system workflow for implant supported full arch prosthesis: a case series, Int. J. Environ. Res. Public Health. 17 (2020) 5038, https://doi.org/10.3390/ijerph17145038.

[32] J.-E. Kim, A. Amelya, Y. Shin, J.S. Shim, Accuracy of intraoral digital impressions using an artificial landmark, J. Prosthet. Dent. 117 (2017) 755–761, https://doi.org/10.1016/j.prosdent.2016.09.016.

[33] K. Lan, B. Tao, F. Wang, Y. Wu, Accuracy evaluation of 3D-printed noninvasive adhesive marker for dynamic navigation implant surgery in a maxillary edentulous model: an in vitro study, Med. Eng. Phys. 103 (2022) 103783, https://doi.org/10.1016/j.medengphy.2022.103783.

[34] X. Pei, X. Liu, S. Iao, F. Ma, H. Li, F. Sun, Accuracy of 3 calibration methods of computer-assisted dynamic navigation for implant placement: an in vitro study, J. Prosthet. Dent. (2022), https://doi.org/10.1016/j.prosdent.2022.03.014. S0022-3913(22)00189-5.

[35] O. González-Martín, E. Lee, A. Weisgold, M. Veltri, H. Su, Contour management of implant restorations for optimal emergence profiles: guidelines for immediate and delayed provisional restorations, Int. J. Periodontics Restorative Dent. 40 (2020) 61–70, https://doi.org/10.11607/prd.4422.

[36] R. Gomez-Meda, J. Esquivel, M.B. Blatz, The esthetic biological contour concept for implant restoration emergence profile design, J. Esthet. Restor. Dent. 33 (2021) 173–184, https://doi.org/10.1111/jerd.12714.